Submillimeter-Wave Radiometer Technology for Earth Remote Sensing Applications

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ABSTRACT

Recent innovations in ultra-high frequency semiconductor device/component technology have enabled both traditional and new applications for space-borne millimeter- and submillimeter-wave heterodyne radiometer instruments. For Earth and planetary remote sensing applications, where system sensitivity is not as much of a driver as it is for astrophysics observations, room-temperature semiconductor diode technology can satisfy most of the receiver front-end noise and bandwidth requirements. Current NASA sponsored submillimeter-wave remote sensing instruments being developed at the Jet Propulsion Laboratory include Earth Observing System Microwave Limb Sounder (EOS-MLS), Microwave Imager for Rosetta Orbiter (MIRO), Cloud Ice and Array Microwave Limb Sounder (AMLS) spanning frequencies from 100 GHz to 2.5 THz. These instruments encompass a variety of new front-end technologies from 100 GHz MMIC amplifiers to novel monolithic membrane diode (MOMED) mixers operating at 2.5 THz. This talk will focus on the specific device, circuit and antenna technology enhancements that are being deployed to meet the needs of the aforementioned NASA programs and highlight potential future technology directions including THz heterodyne imaging.

INTRODUCTION

Submillimeter-wavelength radiometry can enable Earth observations that improve our understanding of climate variability over interannual, seasonal, and decadal time scales, and enhance our knowledge of atmospheric ozone chemistry helping to address three of NASA's Earth Science Enterprise key research areas. Submillimeter-wave radiometry can measure: (1) the amount of ice and the median size and shape of crystals in cirrus clouds, key factors in determining the global radiation balance, (2) upper and middle tropospheric temperature and humidity profiles during cloudy weather, critical data for climate and weather forecast models, (3) abundances and reaction rates of stratospheric and upper tropospheric chemicals like HCl, HF, OH, HO_2, and BrX that impact ozone depletion and global warming and can only be observed at frequencies above 600 GHz.

Heterodyne downconverters (mixers) employing Schottky barrier diodes have formed the heart of spaceborne millimeter, and now submillimeter wave, spectroscopic line receivers for more than 30 years. In 1972 Nimbus 5 was launched and successfully deployed a suite of millimeter-wave radiometers, including a 59 GHz oxygen line receiver for retrieving temperature profiles. Nearly 20 years later NASA's UARS Microwave Limb Sounder extended the upper frequency range of the heterodyne instrumentation to 205 GHz (ozone and ClO), successfully demonstrating both the value of atmospheric limb sounding and the particular resolution and sensitivity advantages offered by signal processing at shorter millimeter wavelengths. Just last year, NASA launched SWAS, the Submillimeter Wave Astronomy Satellite, which contains semiconductor-based heterodyne radiometers at 490 and 550 GHz, now returning impressive amounts of data on water, CO, oxygen and carbon in interstellar space. Currently our group at JPL, along with our industry and University collaborators, are in the final stages of fabricating heterodyne front-ends at 200 and 557 GHz (H_2O, CO) for the Microwave Imager for Rosetta Orbiter (MIRO), an ESA comet flyby mission; at 183, 325, 450 and 640 GHz (H_2O) for Cloud Ice, a DC-8 prototype for an eventual orbital instrument measuring ice crystal sizes and distribution in cirrus clouds; and at 118 (O_2), 190 (H_2O, HCN, HNO_3, SO_2, O_3), 240 (ClO, CO) and 640 GHz (HCl, HO_2, HCN, N_2O, BrO, HOCl) for the EOS Microwave Limb Sounder (EOS-MLS) being launched on NASA's EOS Chemistry platform in 2002. Even more noteworthy, EOS-MLS will contain a completely separate 2500 GHz

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heterodyne radiometer to measure the OH doublet at 119 microns and a nearby water line in the upper stratosphere. The semiconductor technology that has enabled these radiometers has been under development at the Jet Propulsion Laboratory and collaborating university groups for more than 10 years. During this time the detecting devices and submillimeter-wave circuit realizations have improved dramatically, evolving from a fairly unreliable and circuit limiting "cat-whisker" rectifier topology in the early 1990's (implemented on UARS-MLS and SWAS) to a robust, planar-integrated and fairly flexible circuit geometry today. In addition, custom fabricated, ultra-low-parasitic, submicron area, planar GaAs Schottky diodes with cutoff frequencies in excess of 15 THz have extended the operating range and sensitivity of the room temperature mixers to unprecedented levels. Competitive approaches for producing THz radiometers require cryogenic cooling and superconducting devices. The improved sensitivity of such supercooled detector elements may not offset their complexity and cost in spaceborne operation. This was recently demonstrated at 2.5 THz where room temperature semiconductor technology met the EOS-MLS mission requirements [1]. If sensitivity is not the driving force, which it is not for most Earth observations, ambient temperature systems offer significant advantages in cost, complexity and reliability. As space is limited, we will consider only a few of the technology innovations at JPL from the past several years. Within these topics only a few sentences can be accommodated and interested readers are referred to the references for further details.

LOW PARASITIC DIODES USING LINEAR ANODE GEOMETRY (T-ANODES)

The first device innovation that we implemented for our submillimeter wave mixer applications was the replacement of the University of Virginia style plated-up, etched-through SiO-surrounded circular anode [2 e.g.] with a HEMT style T-gate-like linear anode contact [3]. The T-gate geometry reduced both the series resistance and parasitic fringing capacitance of the Schottky diodes by as much as a factor of two, allowing much higher cutoff frequencies to be realized. This T-anode geometry has become a mainstay for all of our THz diode fabrication work at JPL and has been employed to produce anodes with total area of less than 0.1 micron (Fig. 1) and series resistance below 15 ohms on $5x10^{18}$ epi material for mixing at 2.5 THz [4]; in dual and quad diode arrays (Figs 2-3) for frequency multiplying at 300 [5] and 600 GHz [6]; and most recently as a matching element for multiplication at 2700 GHz.

SUBMILLIMETER PLANAR DIODE CIRCUITS ON LOW-DIELECTRIC CONSTANT SUBRATES (QUID)

A second problem that had to be addressed in order to scale traditional sensor components to higher frequencies is the issue of over moding in high dielectric constant materials like GaAs when wafer thickness or reasonable chip handling dimensions reach a significant portion of a wavelength. In lens coupled circuits, especially at cryogenic temperatures, this problem was nicely solved by utilizing shaped thick dielectric substrates [7 e.g.]. However at room temperature, substrate losses in thick lenses become very large and enclosed TEM mode striplines on GaAs must be made very small (<40x80 μm cross section) to maintain single mode operation at 650 GHz. A partial reprieve can be realized by replacing the GaAs substrate with lower loss, lower dielectric constant quartz if a process can be utilized which allows the substitution to occur on a wafer scale. Such an innovation was implemented both at University of Virginia and at JPL in early 1994 with the advent of the QUID (quartz upside-down integrated diode) [8]. In this process the Schottky diode is processed through to completion of anode and wire level circuit definition on the epitaxially grown GaAs host wafer. The wafer is then flipped topside down, epoxied onto a quartz carrier and etched through to the metallic wire layer everywhere but in the vicinity of the diode anodes. The resulting circuit (Figs. 4 and 5) is robust and easily handled and allows a 50x100 μm microstrip to remain single moded up to 700 GHz. The QUID diode, which performs at least as well as chip and whisker-contacted diodes, is being deployed at 240, 325, 450, 557 and 640 GHz on MLS, MIRO and Cloud Ice.

THZ MONOLITHIC CIRCUITS (MOMED)

Above 700 GHz, even the quartz substitution process doesn't allow circuit scaling with reasonable dimensions. For the higher THz frequencies we piggybacked off of a membrane circuit concept originally developed at CalTech [9] and implemented a very traditional mixer circuit geometry at 2.5 THz utilizing a GaAs, rather than silicon MEMs process [10]. This GaAs process (MOMED – monolithic membrane diode) allows us to form ultra high frequency T-anode Schottky diodes on 2 and 3 micron thick by 30 micron wide bridges spanning several hundred microns in a stressless realization. The membrane bridge contains the active diode and RF filter circuitry and is surrounded and supported by a readily handled monolithically formed frame that lies completely outside the RF portion of the circuit (Figs. 6-8). The MOMED mixer circuit performs as well as the best competitive whisker contacted structure and we have obtained receiver noise temperatures below 9000K DSB and mixer noise below 3500K DSB for this circuit [1]. The same concept is now being applied to multipliers, in some cases with the substrate frame etched completely away so that the membrane is supported by free standing wires or integrated beam leads, and for harmonic mixers and planar imaging arrays. We eventually hope to incorporate true MEMs circuit elements as controllable tuners and lower frequency amplifiers (using integrated bump bonding techniques) to increase circuit complexity.

SUBMILLIMETER-WAVE MMIC'S (SMMIC'S)

In order to take the next step forward in THz sensor technology - towards a radiometer-on-a-chip concept - we must begin to employ monolithic fabrication techniques that can be used to create both input/output coupling structures (such as feed horns or antenna beam forming networks), RF transmission lines and high quality Schottky diodes in a single series of wafer level operations (Fig. 9). At the same time the coupling together of chips fabricated in separate process steps (such as local oscillator sources for mixing or intermediate frequency amplifiers for backend processing) must be properly dealt with. Wire bonding is not an effective solution at these frequencies and new MEMs techniques just now coming on line are likely to be required for interchip alignment and coupling. Plans exist at JPL for fabricating 3 dimensional transmission line circuits using deep RIE (reactive ion etch) in GaAs, combined with lithographic processing with SU8, a thick photoresist that has already been proven to yield remarkably small and straight walled circuit elements with dimensions suited for THz frequencies. Resolution is still an issue with SU8 and concepts for joining together chips in a manner which allows lossless passage of RF power across edges have yet to be demonstrated. Some recent success with integrated bump bonds for amplifiers near 100 GHz [11] may solve the near term problems associated with getting high quality IF amplifiers coupled to RF diode wafers (Fig. 10). Also, amplifiers themselves are marching upwards in frequency and may some day replace diode elements in the initial detection stage [12 e.g.].

IMAGING (SUBMILLIMETER CAMERA)

Finally, an ultimate goal of any sensor technology is the realization of true imaging, and a submillimeter camera is still a long way off. However, the MOMED techniques that we have already demonstrated with individual pixels can readily be combined to produce (at least in theory) modest sized heterodyne imagers at THz frequencies. Such an imaging scheme is shown in Fig. 11, where an 80 element array of individually addressed slot antennas, each containing an integrated Schottky diode and fabricated on a GaAs membrane is depicted [13]. The 80 IF amplifiers are arranged in a square surrounding the RF portion of the circuit and fed by microstrip IF lines. LO and RF are input from both sides through a novel diplexer arrangement and beam forming is performed via an external mirror.

SUMMARY

The age of monolithic THz receivers is close upon us. Focused funding by NASA sponsors has resulted in major steps forward in traditional Schottky diode sensor technology and promises much further improvements in the near future. Radiometer-on-a-chip and imaging array concepts are near at hand and will enable new science in the years to come.

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FIGURES

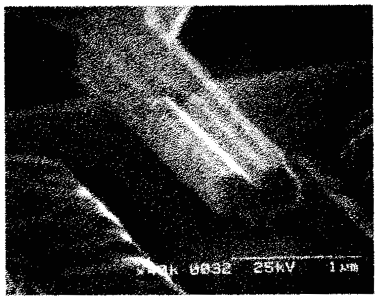

Fig.1. 2.5 THz T-anode 0.1x1µm

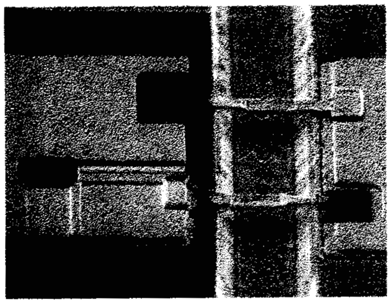

Fig. 2. 640 GHz Back-Back Diodes

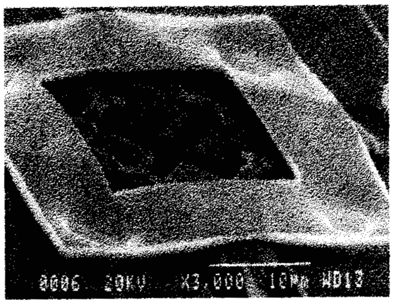

Fig. 3. Planar Quad-Diode Array

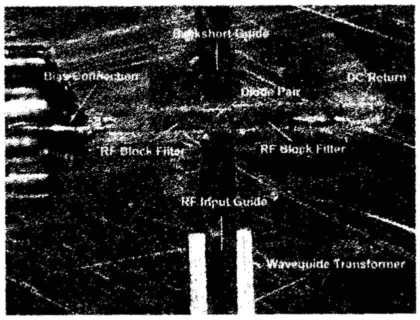

Fig. 4. 640 GHz QUID in Mixer Block

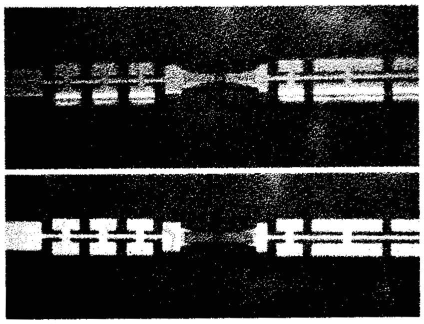

Fig. 5. Bottom/Top View of 540 GHz QUID

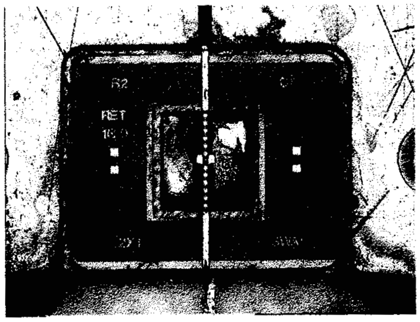

Fig. 6. 2.5 THz MOMED in Mixer Block

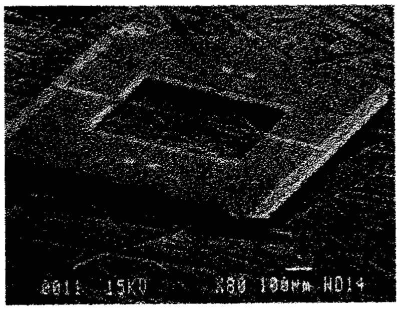

Fig. 7. MOMED with GaAs Frame

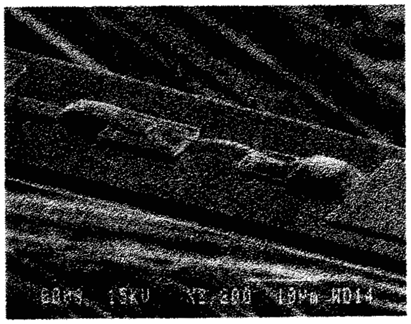

Fig. 8. 2.5 THz Diode on 3µm Thick Bridge

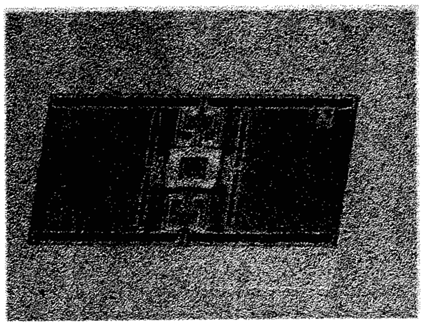

Fig. 9. 600 GHz Quasi-Optic MMIC Multiplier

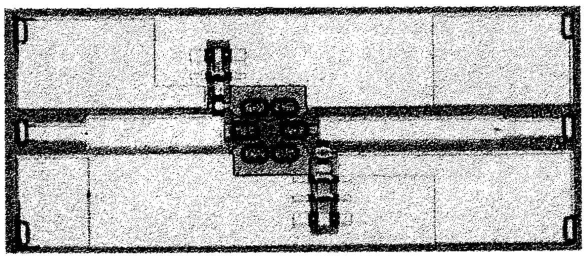

Fig. 10. 100 GHz MMIC Chip with Amp. Bump Bonds

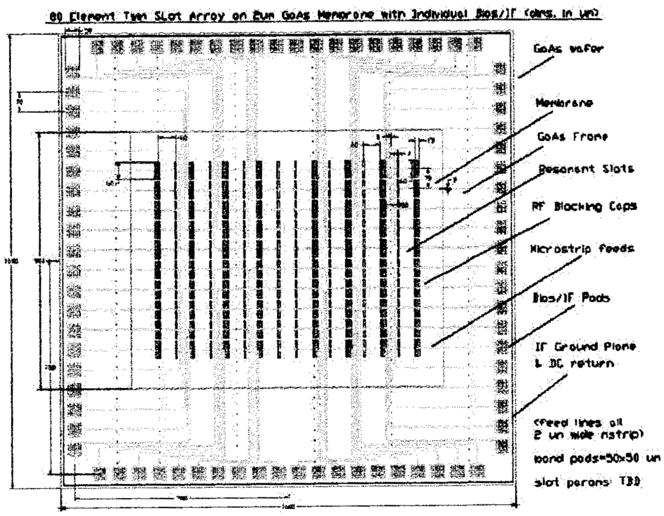

Fig. 11. (Right) Proposed 2.5 THz, 80 Element, Monolithic Heterodyne Imaging Slot Array using MOMED technology